ABERRATION CORRECTING OPTICAL SYSTEM

FIELD OF THE INVENTION AND RELATED ART

This invention relates to an optical system
for correcting aberration of a projection optical
system, for use in a projection exposure apparatus
(mask aligner) for manufacture of semiconductor
devices, for example, to thereby assure better optical
characteristics.

The need for higher density of a
semiconductor device such as IC or LSI has been
increased more and more. In reduction type projection
exposure apparatuses (steppers) wherein an image of a
circuit pattern of a mask (reticle) is formed on a
photosensitive substrate (wafer) through a projection
optical system and the photosensitive substrate is
exposed in accordance with a step-and-repeat method,
or in reduction type projection exposure apparatuses
(scanners) wherein a photosensitive substrate is
exposed with a circuit pattern of a mask (reticle) in
accordance with a step-and-scan method, many
improvements have been attempted in respect to the
resolution of a projection optical system and the
precision of pattern registration for repeated
projection exposures, printing different patterns upon
the same region, to thereby meet the requirements of
higher density integration.

In projection exposure apparatuses, the resolving performance of a projection optical system in relation to a pattern image as well as the pattern registration precision rely upon many factors such as optical performance of the projection optical system, stage precision, alignment precision, and so on. The optical performance of a projection optical system which directly concerns the registration precision involves a projection magnification error and distortion.

On the other hand, because of recent advancement in the optical design technique, it becomes possible to design a projection optical system having a large numerical aperture and a wide exposure region, yet with very small residual aberration.

Practically, however, a projection optical system for an exposure apparatus, as a product, will have aberrations attributable to errors in relation to an optical material or materials used, or to errors involved in the machining or assembling of optical systems, in addition to the residual aberration remaining in design. In consideration of this, in the manufacture of a projection optical system for an exposure apparatus, fine adjustments for various components are made after the assemblage is once completed, to minimize the aberration of the projection optical system due to any errors in

manufacture, to a predetermined level.

Japanese Laid-Open Patent Application, Laid-Open No. 121816/1989, shows an example of fine adjustment of aberration of a projection system, wherein an aberration adjusting optical system comprising a light transmissive parallel flat plate is inserted onto an optical path between an image side of a projection optical system, having telecentricity, and an imaging plane thereof, to thereby adjust spherical aberration and on-axis comma aberration of the projection optical system. In this structure, the spherical aberration of the projection optical system can be adjusted by changing the thickness of the parallel flat plate, while the on-axis comma aberration can be adjusted by tilting the parallel flat plate.

Japanese Laid-Open Patent Application, Laid-Open No. 27743/1998, shows another example of fine adjustment of aberration of a projection system, wherein an aberration adjusting optical system is provided on an optical path between an image side of a projection optical system, having telecentricity, and an imaging plane thereof. The aberration adjusting optical system comprises two parallel flat plates having the same refractive index and the same thickness and being inclined with respect to an optical axis in opposite directions and by the same

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angl , means for changing the tilt angles of these two
transparent flat plates in opposite directions and by
the same amount, means for rotating the whole
adjusting optical system integrally about the optical
5   axis of the projection optical system, and means for
tilting the whole adjusting optical system integrally
in a desired direction. This aberration adjusting
optical system adjusts spherical aberration, on-axis
astigmatism, and on-axis comma aberration,
10   individually.

On the other hand, a registration error in an
exposure apparatus is produced as a consequence (D) of
all of or a part of an alignment error component (A),
an image distortion (distortion) error component (B),
15   and a magnification error component (C). Among them,
the alignment error component can be removed by
relative positional adjustment (alignment) of a
reticle and a wafer. However, the image distortion
error component (B) and the magnification error
20   component (C) can not be removed by the alignment
adjustment. Thus, reduction of these imaging errors
is strongly required for exposure apparatuses.

In regard to evaluation of an image
distortion error component and a magnification error
25   component such as described above, a component
being isotropic around an optical axis of a projection
optical system and being in first-order proportion to

the distance in radial direction from the optical axis, is defined as a magnification error component. On the other hand, the image distortion component (B) can be classified into some components such as a third-order component (B1) proportional to a cube of "h", a fifth-order component (B2) being proportional to a fifth power of "h", and a component (aspect magnification error) (B3) concerning a difference in magnification between two orthogonal directions upon an image plane, for example.

Among these image distortion components, no aspect magnification error (B3) is produced, in design, in a projection optical system which is revolutionally symmetrical with respect to an optical axis. If, however, the surface of the product is not completely revolutionally symmetrical due to any errors in lens production, particularly in a case where the curvature radius of a lens changes along its circumferential direction, there occurs an aspect magnification difference (B3) as an ordinary image distortion component.

An aspect magnification error (B3) of a product projection optical system may be reduced by adjusting some lenses on the basis of: measuring the shapes of the surfaces of the lenses of the projection optical system by use of an interferometer, for example, and performing simulations for rotating the

lenses about an optical axis so that the aspect
magnification error and the on-axis astigmatism of the
projection optical system can be minimized, in total,
due to cancellation by the elements of the projection

5 optical system. However, practically it is still
difficult to suppress both of the aspect magnification
error and the on-axis astigmatism, to a very low level
at the same time.

Japanese Laid-Open Patent Application, Laid-

10 Open No. 183190/1995, shows a projection exposure
apparatus having an illumination optical system for
illuminating a reticle and a projection optical system
for projecting a pattern of the reticle, illuminated
with the illumination optical system, onto a wafer at

15 a predetermined reduction magnification. Optical
means having a refracting power which is
revolutionally asymmetrical with respect to an optical
axis of the projection optical system, is disposed
between the reticle and the wafer. This optical means

20 is made rotatable about the optical axis of the
projection optical system or it is made movable along
the optical axis of the projection optical system, so
as to correct any optical characteristic remaining in
the projection optical system and being revolutionally

25 asymmetrical with respect to the optical axis.
However, on-axis comma aberration such as described
above can not be corrected with this optical means.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an optical system by which on-axis comma aberration or an aspect magnification error can be corrected.

It is another object of the present invention to provide a projection exposure apparatus having such an optical system.

In accordance with a first aspect of the present invention, there is provided an aberration changing optical system for changing an aberration, characterized by an optical element having at least one of a cylindrical surface and a toric surface and being rotatable about and tiltable to an optical axis of said optical system.

In accordance with a second aspect of the present invention, there is provided an aberration changing optical system for changing an aberration, characterized by an optical element having different refracting powers in two orthogonal directions (or sectional planes) or having a refracting power only in one direction, said optical element being rotatable about and tiltable to an optical axis of said optical system.

In these aspects of the present invention, there may be a plurality of optical elements each being as aforesaid, and wherein said optical elements

are selectively used.

There may be a second optical element having at least one of a cylindrical surface and a toric surface and being rotatable about and tiltable to the optical axis of said optical system integrally with the first-mentioned optical element, said second optical element further being tiltable in an opposite direction to the first-mentioned optical element.

There may be a parallel flat plate being rotatable about and tiltable to said optical axis of said optical system integrally with the optical element, said parallel flat plate further being tiltable in an opposite direction to said optical element.

The optical element may be mainly composed of a transparent material such as quartz or fluorite, for example.

The or each surface of said optical element, having a refracting power, may have a refractive power not greater than $3 \times 10^{-7} mm^{-1}$.

In accordance with a third aspect of the present invention, there is provided a projection system, comprising: a projection optical system; and an aberration changing optical system as described above, for correcting an aberration to be produced in said projection optical system.

In accordance with a fourth aspect of the

present invention, there is provided a projection exposure apparatus, comprising: an illumination system; and a projection system for projecting a pattern of a mask onto a substrate in cooperation with said illumination system, said projection system including a projection optical system and an aberration changing optical system, as described above, for correcting an aberration to be produced in said projection optical system.

In accordance with a fifth aspect of the present invention, there is provided a device manufacturing method, including a process for transferring a device pattern onto a wafer by use of a projection exposure apparatus as described above.

In accordance with a sixth aspect of the present invention, there is provided an optical system characterized by an optical element having at least one of a cylindrical surface and a toric surface and being inclined with respect to an optical axis.

In accordance with a seventh aspect of the present invention, there is provided an optical system characterized by an optical element having different refracting powers in two orthogonal directions (or sectional planes) or having a refracting power only in one direction, said optical element being inclined with respect to an optical axis.

In the sixth and seventh aspects of the

present invention, described above, there may be a plurality of optical elements each being as aforesaid, and wherein said optical elements are selectively used.

Also, there may be a second optical element having at least one of a cylindrical surface and a toric surface and being inclined with respect to the optical axis and in an opposite direction to the first-mentioned optical element.

There may be a parallel flat plate being inclined with respect to the optical axis and in an opposite direction to said optical element.

The optical element may be mainly composed of a transparent material such as quartz or fluorite, for example.

The or each surface of said optical element, having a refracting power, may have a refractive power not greater than $3 \times 10^{-7} \mathrm{mm}^{-1}$.

In accordance with an eights aspect of the present invention, there is provided a projection system, comprising: a projection optical system; and an optical system according to the sixth or seventh aspect of the present invention, for correcting an aberration to be produced in said projection optical system.

In accordance with a ninth aspect of the present invention, there is provided a projection

exposure apparatus, comprising: an illumination
system; and a projection system for projecting a
pattern of a mask onto a substrate in cooperation with
said illumination system, said projection system
5   including a projection optical system and an optical
system according to the sixth or seventh aspect of the
present invention, for correcting an aberration to be
produced in said projection optical system.

In accordance with a tenth aspect of the
10   present invention, there is provided a device
manufacturing method, including a process for
transferring a device pattern onto a wafer by use of a
projection exposure apparatus as described just above.

These and other objects, features and
15   advantages of the present invention will become more
apparent upon a consideration of the following
description of the preferred embodiments of the
present invention taken in conjunction with the
accompanying drawings.

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BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic view for explaining
an aberration adjusting optical system according to an
embodiment of the present invention.

25   Figure 2 is a schematic view of a projection
exposure apparatus according to an embodiment of the
present invention.

Figure 3 is a schematic view of an aberration adjusting optical system according to another embodiment of the present invention.

Figure 4 is a schematic view of an aberration adjusting optical system according to a further embodiment of the present invention.

Figure 5 is a flow chart of semiconductor device manufacturing processes.

Figure 6 is a flow chart for explaining details of a wafer process, included in the procedure of Figure 5.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 is a schematic view of an aberration adjusting optical system according to a first embodiment of the present invention, and it shows optical paths in a portion of a projection system having such aberration adjusting optical system.

As shown in Figure 1, there is an aberration changing optical system 13 comprising an anamorphic optical element and being disposed between an image plane 12 of a projection optical system 17 and a lens 11, of the projection optical system 17, which is closest to the image plane thereof. The optical element 13 is rotatable about an optical axis and also is tiltable about an axis perpendicular to the optical axis. Also, the optical element 13 is mainly composed

of a transparent material such as quartz or fluorite,
for example, having a high transmission factor with
respect to light of a wavelength greater than 250 nm.

In Figure 1, the projection optical system 17
5 is telecentric on its image plane side, and the
orientation of chief rays of imaging lights is
parallel to an optical axis 14. A projection optical
system of an exposure apparatus, for example, for use
in manufacture of semiconductor devices may preferably
10 comprise such an optical system being telecentric on
its exit side, to prevent a change in imaging
magnification of a device pattern image, depending on
the wafer surface position with respect to the optical
axis direction.

15 In this embodiment, the aberration changing
optical system includes an optical element 13 which
has different refracting powers with respect to
orthogonal directions. The optical element 13 is made
rotatable about the optical axis, and also it is made
20 tiltable about an axis perpendicular to the optical
axis, by which any aspect magnification error of the
projection system can be adjusted.

As regards the provision of the optical
element with a refracting power only in one direction,
25 a cylindrical surface or a diffractive surface such as
a binary optics (BO) element may be used. The surface
that applies a refracting power may be defined only on

one surface of the optical element at the image side
or object side thereof. Alternatively, both surfaces
may be formed to have a refracting power in the same
direction.

5   In a case where the aberration changing
optical system 13 which comprises a single optical
element (13) has a surface 13a, on the object side,
and a surface 13b, on the image side, which are flat
and are disposed in parallel to each other (i.e., a
10 case of a parallel flat plate), a single chief ray 15
impinges at a reference position 12a upon the image
plane 12, spaced from the optical axis 14 by a
distance d_0.

         The aberration changing optical system 13 of
15 this embodiment is formed with an object side surface
13a being flat and an image side surface 13b of a
cylindrical surface having a convex shape toward the
image side and having a very large curvature radius r.
The generating line of the cylindrical surface extends
20 in a Y-axis direction. Thus, by rotating it around
the optical axis and by tilting it about an axis
parallel to the generating line and perpendicular to
the optical axis, the aspect magnification difference
can be changed, such that adjustment of aspect
25 magnification of the projection system is
accomplished.

         When a chief ray 15 is refracted by the

cylindrical surface 13b and where the largest image height of the projection optical system 17 is h_{max} and the refractive index of the glass material (material) of the aberration changing optical system 13 is n, the angle θ_0 of light emitted therefrom, with respect to the chief ray 15, can be expressed by the following equation:

$$\theta_0 \fallingdotseq (n-1) \cdot h_{max}/r \qquad \ldots (1)$$

Further, where the distance from the cylindrical surface 13b to the image plane 12 is S_k, the amount of shift Δd of the imaging position, upon the image plane 12 as the chief ray 16 impinges on the image plane 12, from the reference position 12a thereon can be given by:

$$\Delta d \fallingdotseq S_k \theta_0 \fallingdotseq (n-1) \cdot S_K \cdot h_{max}/r \qquad \ldots (2)$$

The shift amount Δd above corresponds to a change in imaging magnification.

On the other hand, as regards the position of incidence, upon the image plane, of the chief ray with respect to the generating-line direction (Y direction) perpendicular to the direction (X direction) of the curvature r of the cylindrical surface 13b, since the chief ray is not refracted by the cylindrical surface 13b in the Y direction, it does not shift from the reference position 12a. Thus, no change occurs in the imaging magnification. In accordance with the principle described above, the imaging magnification

can be changed only in the direction (X direction) in which the cylindrical surface 13b has a curvature, and thus correction of aspect magnification difference of the projection optical system 17 is accomplished.

5   In this embodiment, where the distance S_k from the cylindrical surface 13b to the image plane is 36 mm, the largest image height h_{max} of the projection optical system 17 is 15.6 mm, the refractive index n of the material of the aberration changing optical
10   system 13 is 1.5, and the aspect magnification difference (a difference at the largest image height position) which can be adjusted through the aberration adjusting optical system 13 is 0.05 micron, then, from equation (2), the curvature radius r required for the
15   cylindrical surface 13b is about 5.0×10^6 mm.

Here, the refracting power ϕ to a light ray passing through the cylindrical surface 13b can be given by the following equation:

$$\phi = |(n-r)/r| \qquad \ldots (3)$$

20   The refracting power ϕ above takes a positive value only, as a common definition for the light entrance side surface and the light exit side surface of the aberration changing optical system 13. The refracting power of the cylindrical surface 13b in the
25   above-described embodiment is, from equation (3), $\phi = 1.0 \times 10^{-7} \text{mm}^{-1}$. If the refracting power ϕ is sufficiently small, an additional aberration amount

other than the aspect magnification differenc through the aberration changing optical system 13 is small, such that there occurs no problem in practice. If, on the other hand, the refracting power ϕ becomes larger than $\phi = 3.0 \times 10^{-7} mm^{-1}$, the addition of other aberration through the aberration changing optical system 13 becomes notable and can not be disregarded. Therefore, preferably a condition $\phi \leq 3.0 \times 10^{-7} mm^{-1}$ should be satisfied.

On the other hand, it will be readily understood that, even if the refracting power is sufficiently weak, not only the aspect magnification difference but also other aberrations such as a spherical aberration, which are influential to the imaging characteristic, are produced due to the aberration changing optical system 13. Therefore, it is necessary to design the projection optical system 17 while taking into account the influence of the aberration changing optical system 13. Further, in consideration of the property that the spherical aberration of the projection optical system 17 depends on the thickness of the aberration changing optical system 13, the spherical aberration of the projection optical system 17 as a product may be measured in practice and then a best thickness of the aberration changing optical system 13 may be determined. Further, the on-axis comma aberration of the

projection optical system 17 may be measured and, on
the basis of the result thereof, a best tilt angle of
the aberration changing optical system 13 may be
determined. Then, by tilting the aberration changing
5   optical system 13 about an axis orthogonal to the
optical axis, the on-axis comma aberration can be
adjusted.

Figure 2 illustrates an optical arrangement
having an aberration adjusting optical system
10   according to an embodiment of the present invention,
wherein the optical system of the present invention is
incorporated into a projection exposure apparatus for
semiconductor device manufacture. This embodiment can
be applied to a projection exposure apparatus of
15   either a step-and-repeat type or a step-and-scan type.

Denoted in Figure 2 at 21 is a light source
which comprises a laser such as an excimer laser.
Denoted at 22 is an illumination optical system for
uniformly illuminating a reticle 23 (surface to be
20   illuminated) with light from the light source 21.
Denoted at 23 is a reticle, and denoted at 24 is a
projection lens for projecting a pattern of the
reticle 23 onto a wafer 24 in a reduced scale.
Denoted at 25 is the surface of the wafer which is
25   placed on the image plane.

There is an aberration changing optical
system 13 such as described with reference to Figure

1, which is disposed between the projection lens 24
and the wafer 25. The aberration changing optical
system 13 can be rotated around the optical axis and
also tilted about any axis orthogonal to the optical

5   axis, by means of a driving system 130 or manually.
With this structure, aberrations of the mask
projecting system including the projection optical
system 24 and the optical system 13 can be adjusted.

Figure 3 is a schematic view of a main
10   portion of an aberration changing optical system
according to a second embodiment of the present
invention. In this embodiment, the aberration
changing optical system 13 comprises two optical
elements 311 and 312 having the same refractive index

15   and the same thickness and being inclined with respect
to the optical axis by the same angle but in opposite
directions.

The first optical element 311 placed at the
object side has a surface 311a on the object side and

20   a surface 311b on the image side which are flat and
are disposed in parallel to each other. The second
optical element 312 placed at the image side has a
flat surface 312a on the image side and a cylindrical
surface 312b, on the image side, of convex shape

25   facing toward the image side.

Further, there are first rotating means for
rotationally moving the second optical element 312,

having a protruded cylindrical shape on one surface
thereof, about an axis perpendicular to its flat
surface 312a, and first tilting means for changing the
tilt angles of the two optical elements 311 and 312 in
5 opposite directions but by the same amount.
Additionally, there are second rotating means for
rotationally moving the whole aberration changing
optical system 13 integrally about the optical axis of
the projection optical system, and second tilting
10 means for tilting the whole aberration changing
optical system integrally in a desired direction.

    With use of the aberration changing optical
system of this embodiment, in addition to the aspect
magnification error, other aberrations such as a
15 spherical aberration, an on-axis comma aberration and
an on-axis astigmatism, for example, can be adjusted.

    More specifically, the aspect magnification
error can be adjusted in accordance with the same
principle as in the first embodiment. The spherical
20 aberration can be adjusted by changing the central
thickness of the two optical elements 311 and 312, by
changing one by another. The on-axis astigmatism can
be adjusted by rotating the aberration changing
optical system 13 as a whole integrally, about the
25 optical axis of the projection optical system, and by
changing the tilt angles of the two optical elements
311 and 312 in opposite directions and by the same

amount. Further, the on-axis comma aberration can be adjusted by tilting the aberration changing optical system 13 integrally.

An example of aspect magnification error adjustment through the optical system 13 of this embodiment, will be explained with reference to Figure 1 and in respect to specific numerical data.

In this example, the distance S_k from the cylindrical surface 312b to the image plane is 36 mm, the largest image height h_{max} of the projection optical system is 15.6 mm, the refractive index n of the materials of the optical elements 311 and 312 is 1.5, and the aspect magnification difference at the largest image height position which can be adjusted by the aberration changing optical system 13 of this embodiment is 0.05 micron. The required curvature radius r of the cylindrical surface 312b can be calculated in accordance with equation (2), as in the first embodiment, and it is about 5.0×10^6 mm.

In a case where the central thickness of the two optical elements 311 and 312 of the aberration changing optical system 13, in the optical axis direction, is 8 mm, the air spacing between the two optical elements 311 and 312 is 2 mm, the exposure wavelength is 248 nm, and the numerical aperture of the projection optical system 17 is 0.6, and when the tilt angles of the two optical elements 311 and 312

are changed in opposite directions by 10',
respectively, the on-axis astigmatism of the
projection optical system changes by about 0.06
micron.

5   While this embodiment has been described with
reference to an example where the first optical
element 311 of the aberration changing optical system
comprises a parallel flat plate and the second optical
element 312 thereof has a one-side cylindrical
10   surface, the invention is not limited to this. The
first optical element may have a cylindrical surface
on one side thereof, and the second optical element
may comprise a parallel flat plate.

          Figure 4 is a schematic view of a main
15   portion of an aberration changing optical system
according to third embodiment of the present
invention. In this embodiment, the aberration
changing optical system 13 comprises two optical
elements 411 and 412 having the same refractive index
20   and the same central thickness and being tilted with
respect to the optical axis, in opposite directions
and by the same angle.

          The first optical element 411 placed on the
object side has a flat surface 411a on the object side
25   and a cylindrical surface 411b, on the image side, of
convex shape facing toward the image side. Similarly,
the second optical element 412 placed on the image

side has a flat surface 412a on the object side and a cylindrical surface 412b, on the image side, of convex shape facing toward the image side.

The aberration changing optical system 13 of this embodiment is provided with first rotating means for rotationally moving these two optical elements 411 and 412 about an axes perpendicular to their flat faces 411a and 412a, respectively, and first tilting means for changing the tilt angles of the two optical elements in opposite directions but by the same amount. Additionally, there are second rotating means for rotationally moving the whole aberration changing optical system 13 integrally, about the optical axis of the projection optical system, and second tilting means for tilting the whole aberration changing optical system integrally, in a desired direction.

With the aberration changing optical system of this embodiment, by rotating the first optical element 411 about an axis perpendicular to its flat surface 411a and by rotating the second optical element 412 about an axis perpendicular to its flat surface 412a, respectively, a change in magnitude and direction of the aspect magnification difference can be adjusted.

More specifically, as the direction in which the cylindrical surface 411b of the first optical element 411 has a curvature is brought into

registrati n with the direction in which the
cylindrical surface 412b of the second optical element
412 has a curvature, the amount of change in aspect
magnification difference becomes maximum.   If it is
5   made orthogonal to the direction in which the
cylindrical surface 412b of the second optical element
412 has a curvature, the amount of change in aspect
magnification difference becomes smallest.

An example of adjustment of an aspect
10   magnification error in this embodiment will be
described with reference to Figure 1 and in respect to
specific numerical data.

In this example, simulations were made with
the conditions that: the exposure wavelength is 248
15   nm, the numerical aperture of the projection optical
system is o.6, the central thickness of the two
optical elements 411 and 412 of the aberration
changing optical system in the optical axis direction
is 8 mm, the air spacing between the two optical
20   elements 411 and 412 is 2 mm, the curvature radius of
the cylindrical surface 411b of the first optical
element 411 is 6.0×10^6 mm, the curvature radius of the
cylindrical surface 412b of the second optical element
412 is 5.0×10^6 mm, the distance S_k from the
25   cylindrical surface 412b of the second optical element
412 to the image plane is 36 mm, the largest image
height h_{max} of the projection optical system is 15.6

mm, the refractive index n of the materials of the optical elements 411 and 412 is 1.5.

As a result, it has been confirmed that, when the direction in which the cylindrical surface 411b of the first optical element 411 has a curvature and the direction in which the cylindrical surface 412b of the second optical element 412 has a curvature, are placed orthogonal to each other, the aspect magnification difference imparted by the aberration changing optical system becomes equal to zero.

On the other hand, when the first optical element 411 and/or the second optical element 412 is rotated about an axis perpendicular to its flat surface so that the direction in which the cylindrical surface 411b of the first optical element 411 has a curvature and the direction in which the cylindrical surface 412b of the second optical element 412 has a curvature are brought into registration with each other, the amount of aspect magnification difference imparted by the aberration changing optical system 13 becomes maximum. The amount of change thereof at the largest image height position is 0.11 micron.

The angle defined between the direction in which the cylindrical surface 411b of the first optical element 411 has a curvature and the direction in which the cylindrical surface 412b of the second optical element 412 has a curvature, can be adjusted

as desired. Here, the aspect magnification difference
to be imparted by the aberration changing optical
system varies continuously from zero to a maximum.
Thus, within a range from zero to an adjustable

5   largest value, the aspect magnification difference in
a desired amount and direction to be produced by the
projection optical system can be adjusted through the
aberration changing optical system of this embodiment.
Further, like the second embodiment, the spherical

10 aberration, the on-axis comma aberration and the on-
axis astigmatism of the projection optical system can
be adjusted independently of each other, as desired.

Although the foregoing embodiments have been
described with reference to a case where the image

15 side surface of an optical element, constituting the
aberration changing optical system, has a refracting
power, the invention is not limited to this form. The
object side surface may have a refracting power, or
both of the object side surface and the image side

20 surface may have a refracting power in the same
direction.

Providing a refracting power in one direction
of the optical element is not limited to use of a
smooth cylindrical surface shape. A diffractive

25 optical element such as a binary optics (BO) having a
one-dimensional refracting power may be used, for
example.

Alternatively, an anamorphic optical system having different refracting powers in X and Y directions may be used for the aberration changing optical system. As regards the central thickness of the optical element used in the aberration changing optical system, if it is not greater than 5 mm, any additional aberration will be produced due to the influence of weight deformation of the optical element. If it is not less than 30 mm, there will occur absorption of exposure light by the optical element. Thus, preferably it may be in a range from 5 mm to 30 mm. Further, in a case where the aberration changing optical system comprises plural optical elements, in order to avoid Newton's rings resulting from interference of light inside the optical system. an air spacing of 0.1 mm or more should preferably be maintained between adjacent optical elements.

Further, the specifications of a projection optical system having an aberration changing optical system of the present invention incorporated therein, such as the exposure wavelength and the numerical aperture, for example, are not limited to those described hereinbefore.

Next. an embodiment of a device manufacturing method which uses an exposure apparatus having a projection optical system with an aberration changing optical system, according to any one of the preceding

embodiments, will be explained.

Figure 5 is a flow chart of procedure for
manufacture of microdevices such as semiconductor
chips (e.g. ICs or LSIs), liquid crystal panels. or
5   CCDs, for example.

Step 1 is a design process for designing a
circuit of a semiconductor device. Step 2 is a
process for making a mask on the basis of the circuit
pattern design. Step 3 is a process for preparing a
10   wafer by using a material such as silicon. Step 4 is
a wafer process (called a pre-process) wherein, by
using the so prepared mask and wafer, circuits are
practically formed on the wafer through lithography.
Step 5 subsequent to this is an assembling step
15   (called a post-process) wherein the wafer having been
processed by step 4 is formed into semiconductor
chips. This step includes an assembling (dicing and
bonding) process and a packaging (chip sealing)
process. Step 6 is an inspection step wherein
20   operation check, durability check and so on for the
semiconductor devices provided by step 5, are carried
out. With these processes, semiconductor devices are
completed and they are shipped (step 7).

Figure 6 is a flow chart showing details of
25   the wafer process.

Step 11 is an oxidation process for oxidizing
the surface of a wafer. Step 12 is a CVD process for

forming an insulating film on the wafer surface. Step 13 is an electrode forming process for forming electrodes upon the wafer by vapor deposition. Step 14 is an ion implanting process for implanting ions to the wafer. Step 15 is a resist process for applying a resist (photosensitive material) to the wafer. Step 16 is an exposure process for printing, by exposure, the circuit pattern of the mask on the wafer through the exposure apparatus described above. Step 17 is a developing process for developing the exposed wafer. Step 18 is an etching process for removing portions other than the developed resist image. Step 19 is a resist separation process for separating the resist material remaining on the wafer after being subjected to the etching process. By repeating these processes, circuit patterns are superposedly formed on the wafer.

With these processes, high density microdevices can be manufactured.

While the invention has been described with reference to the structures disclosed herein, it is not confined to the details set forth and this application is intended to cover such modifications or changes as may come within the purposes of the improvements or the scope of the following claims.